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Managing Pollution Control in Brazil

The Potential Use of Taxes and Fines by Federal and State Governments

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and
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Federal monitoring of decentralized (state) environmental management — through a system of pollution-based fines and taxes assigned respectively to the federal and state governments — can improve firms' compliance and environmental agency performance without damaging state revenue, and perhaps even improve it.

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This paper — a product of the Infrastructure Division, Country Department I, Latin America and the Caribbean — is part of a larger effort in the region to design specific reforms that can assist governments in decentralized economies, such as Brazil or Venezuela, in dealing with unusual sources of policy failures in the area of pollution control. Copies of the paper are available free from the World Bank, 1818 H Street NW, Washington, DC 20433. Please contact Antonio Estache, room E10-081, extension 81442 (July 1992, 46 pages).

Estache and Zheng make a case for federal monitoring of state environmental agencies' (SEPAs') performance — because of the tradeoff for the states between the need to raise revenue from taxes on local output and the need to limit pollution.

They also show that fines and taxes assigned respectively to the federal and state governments can improve firms' compliance and SEPA's performance — and hence environmental quality — without damaging state revenue, and perhaps even improving it.

They rely for their analysis on numerical policy simulations based on an analytical framework designed as a multilevel Stackelberg game. This framework reproduces the hierarchical structure of pollution control policies in Brazil, where the federal environmental protection agency relies on SEPAs to ensure that federally defined minimum ambient standards are met locally.

The numerical simulations are based on a case study of the food and the printing and publishing industries.

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1. Introduction

Pollution control is highly decentralized in Brazil. State governments are expected to ensure that local water and air quality meet federal minimum ambient standards. This decentralization aims at greater autonomy in the implementation of federal guidelines. States can then select and design instruments, within boundaries defined by the Constitution, to achieve federal objectives. Most states rely on regulations such as licenses or standards to achieve their objectives. Fines on polluters are used commonly by the states but are generally not directly related to the level of pollution. In practice, the success of current policies has been limited as in most of Brazil, pollution is increasing. [1]

Differences in decentralized implementation of federal requirements across states may reflect differences in administrative or financial resources available to monitor polluters. Weak implementation may result from weak effective commitment to the pollution issue by the state or federal governments. States may have multiple objectives and their role as an agent of the federal government may be only one of those objectives. Other goals may include fiscal revenue targets or local jobs creation for instance. Strong enforcement leads to lower output and hence reduces tax revenue, at least in the short run, by reducing the tax base and cutting jobs. Davis and Lester (1989) and Taylor (1990) provide surveys, respectively of the political science and the economic literature, analyzing evidence for the U.S. on the importance of interstate competition for investment or tax revenue based on the degree of enforcement of pollution laws. They show competition is not widespread but that when it occurs, its impact on resource allocation and mobilization is such that it cannot be ignored.

Since the Brazilian experience of the eighties provides ample evidence of tax competition among states to attract jobs and investment across states, the interstate regulatory competition issue in Brazil deserves particular attention. In fact, as in many other decentralized economies, many in Brazilian states administrations would be willing to argue that they face a tradeoff between revenue and environmental quality. The underlying reasoning is as follows. The better a state's enforcement of federal requirements, the less polluted the state is but the lower is state net revenue. Net revenue is lower because output is cut, at least in the short run as capital has to be diverted from production to pollution control. [2] But net revenue is also lower because monitoring is costly and currently only yields trivial penalty returns. This sort of reasoning may explain why the degree of enforcement of pollution laws is often

1. For an overview of issues raised by pollution control policies in Brazil, see Estache (1990).

2. Since the model focuses on the short run, any output effect of technological improvements brought about by investment in pollution control is ruled out.

negotiated between polluter and state environmental agencies and may be one of the sources of deterioration of Brazil's environment. [3]

The paper presents some reforms in the design of this decentralized pollution control management that could result both in improvements in pollution control and in state revenue. It shows how federal inspection of the states' environmental protection agency (SEPAs) performance could reduce the incentive for states to minimize the importance of pollution control. If SEPAs' poor monitoring allows the firms to pollute more, the SEPAs should be penalized by the federal government or its representative, the federal environmental protection agency (FEPA). The penalty could be a fine or could be a reduction in federal transfers. Another reform that should be considered is the introduction of a pollution tax to be collected by the states. The tax would not only increase the incentive of firms to comply with environmental regulation but also that of the states as pollution revenue would offset the loss from production taxes.

This interpretation of the interactions among agents is essentially impossible to test econometrically as data on the actual behavior of regulated firms, states or federal government in Brazil, as in most countries, are scarce. However, these strategic interactions can be illustrated and analyzed within a game-theoretical framework. It identifies circumstances under which the federal government can induce the firms and the states to comply with its requirements. A priori, these circumstances vary from sector to sector with factors such as pollution intensity of the production activity and the effectiveness of the abatement technology used by the firms. But there are additional factors that contribute to the success of decentralized pollution management. These are illustrated by some simulations discussed in the paper. For instance, since federal monitoring is not costless either, the federal government has to carefully assess circumstances under which it wishes to inspect the states. Firms know it and are likely to adapt their compliance efforts to the likelihood of being audited and to the federal monitoring efforts. Since the federal and states governments are aware of the firms' behavior, they adjust their policies to the firms' reactions.

The rest of the paper is organized as follows. Section 2 explains the choice of the analytical framework reproducing the strategic interactions between the three levels of decisionmakers: FEPA, SEPAs and the firms. It also provides an overview of the major "policy" implications of this framework. Section 3 presents the simulations for two sectors (Paper and Printing and Food) of the various forms of federal

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3. Other issues include instrument selection and policy coordination across ministries. The issues raised by instrument selection are not addressed here specifically although some of the simulations illustrate the potential of fines and pollution taxes to achieve pollution control objectives. A useful survey on instrument selection is provided by Eskeland and Jimenez (1991). Other aspects of policy coordination are reviewed in Jack (1991).

government intervention aiming at improving states and firms compliance with federal requirements. Section 4 summarizes the main policy conclusions and discusses their generality. An analytical presentation of the actual framework is provided as an Annex.

2. A Game-Theoretical Framework to Assess Decentralized Environmental Policy-making

2.1. Motivating the Choice of the Analytical Framework

The institutional organization of pollution management in Brazil involves three levels of agents: the FEPA, the SEPAs and the firms as illustrated by Figure 1. The FEPA relies on SEPAs to enforce federal environmental regulation. SEPAs supervise firms for the FEPA but also see the firms as the source of tax revenue based on their output. Under the current institutional set up in Brazil, better enforcement of federal requirements implies, in the short run, lower output and hence state revenue. This assignment of responsibilities has then a built-in conflict of interest. In practice, the SEPAs do not collect directly the revenue from sales or production taxes, but their resources, including salaries, are paid from these sources of revenue. This is why the incentive structure of the three levels of agents needs to be carefully designed.

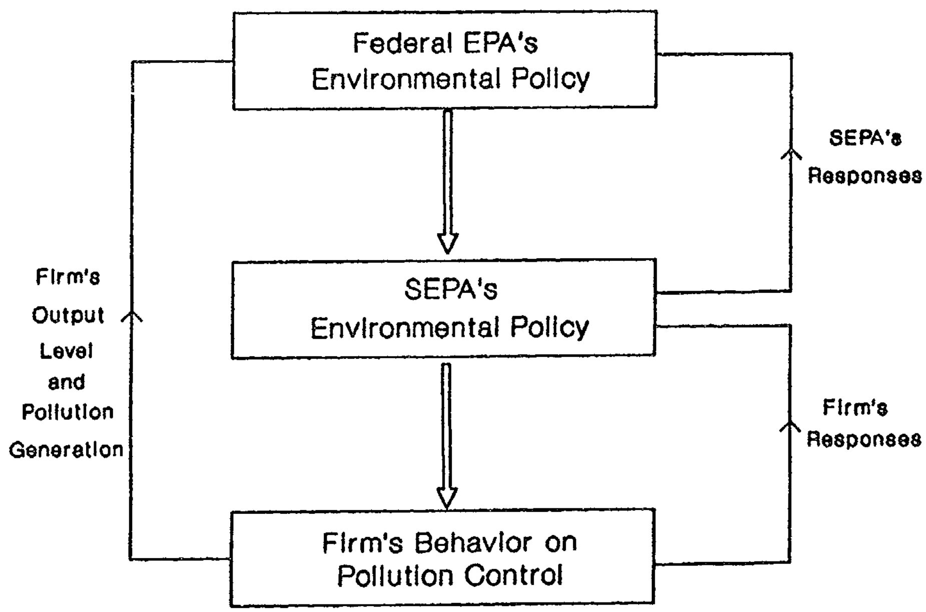

Figure 1 The Policy Design System with Action Responses and Information Feedback

A key aspect of the incentive structure requires an assessment of information asymmetries. There are various sources of information asymmetries among the actors that would require a careful assessment. The source we focus on is the degree of monitoring--i.e how much is the FEPA going to monitor the SEPAs, and how much are the SEPAs going to monitor the firms?--.[4] Because of these asymmetries, Brazil's institutional structure for pollution control can be modeled as a set of multilayer hierachized principal-agent relationships. As pointed out by Tirole (1986), this hierarchal structure does not necessarily boil down to a compounding of the basic production inefficiency built in every pair of principal-agent relationship.[5] This is because this more complex structure introduces the possibility of common interest between the SEPAs and the firms.[6] When the SEPAs perform well as agents for the FEPA, firms' profits are cut and so is states tax revenue. Conversely, the SEPAs can improve both their lot and that of the firms by cutting on enforcement. The design of the incentive structure is further complicated by the fact that there is a limit on the pollution control effort that can be imposed on the firms. The exact limit depends on the extent to which the federal government is willing to trade-off environment quality and growth. Excessive punishment will close business altogether which the federal government does not want either. In other words, there has to be a restriction on the size of the fine and on the monitoring efforts.[7] To figure out the desirable design of pollution management, the federal government has to take the initiative in gathering information on the behavior of the SEPAs and of firms. In game theoretical jargon, the FEPA is a Stackelberg leader, the states and the firms are followers in their relation with the FEPA and the three actors are playing a hierarchical Stackelberg game. Similarly, the SEPA is a Stackelberg leader in its relation with the firms.

2.2. An Overview of the Model and of its Theoretical Policy Implications [8]

The model focuses on the vertical behavioral relationship between the FEPA, a representative SEPA and a representative firm. The FEPA is assumed to know the objectives of the states and firms. States maximize their tax revenue and firms maximize their after-tax profits. These "followers" may know little about the FEPA's

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4. See Russell (1990a, 1990b) for other sources of information asymmetry relevant to the structuring of monitoring and enforcement issues.

5. Holmstrom and Tirole (1989), pp. 106-126, provide an overview of the very limited literature on hierarchies in the theory of the firm.

6. Tirole (1986) deals explicitly with collusion. We do not directly but implicitly as without changes in FEPA's behavior, the SEPAs would have an incentive to alter its behavior in a way that also benefit firms. Laffont (1990) also adds the possibiliiy of the ability of some players to design games with other members of the hierarchy that are not observable to the principal.

7. See Calvo and Wellisz (1978) for a discussion of this limit in the context of the punishment of shirking workers.

8. A full description and discussion of the model is provided in the annex.

intention. They react to the FEPA's strategy selection and then design their optimal response. This reaction process is known to the leader, who takes it into account when it optimizes its own strategy. Through such an independent decision system, the leader uses its own positional advantage to influence the follower's strategy selection and makes it consistent with its own objectives. A similar reasoning is applied to the role of the SEPA as a Stackelberg leader in its relation with firms.

i. The firm's perspective

The firm's problem is as follows. It has a fixed capital stock as this is a short term model. It can use it either to produce or to abate pollution. Its production technology is associated with a pollution function. This function depends on the output level and on the abatement intensity and technology. The "dirtier" the industry and the lower its abatement efficiency, the larger the investment in abatement required to satisfy the environmental protection legislation. Finally, the last component of the firm's problem is the profit function. The firm's profits are affected by two taxes: a value added tax and a possible pollution tax. The pollution tax is based on emissions and can only be levied if the SEPA checks the firm. In sum, it is the "effective" pollution tax that matters. This effective tax is the pollution tax corrected by the probability of the firm to be monitored. If the state never monitors a firm. Its effective tax rate is zero. In practice this is somewhat how fines work in many states in Brazil. A major difference is that fines are not directly related to actual emissions in Brazil. They are more related to the frequency of violation than to the intensity or toxicity. A better solution, currently under consideration in some Brazilian states, could be to relate the tax to potential pollution as derived from the composition--i.e. age, model, ...--of the capital stock. Firms would then get penalized for not adopting a cleaner technology.

Within this framework consisting of the firm's production function, pollution function and profit function, the firm is making a portfolio selection: how to allocate its fixed amount of capital to two different ends to maximize its expected profit? Shifting one unit of capital from production to pollution control has two effects: (a) it generally lowers the firm's output and thus its sales revenue; but (b) it reduces pollution and thus its potential pollution tax.

The firm chooses its investment in abatement by comparing the *marginal cost* (MC) of abating pollution with the *marginal benefit* (MB) of doing so. The marginal benefit is essentially the savings in pollution tax liability stemming from the investment in pollution control. It is determined by the pollution tax and the pollution intensity of the firm. The *marginal cost* is reflected in the loss in after-tax profits due to diversion of resources for pollution abatement. It is determined by the effective pollution tax and the investment in abatement.

The solution of the firm's problem leads to the following--many of them very intuitive--theoretical policy implications: [9]

Policy Implication 1: *If the marginal cost of abatement is greater than the marginal benefit, then the firm will abate less.*

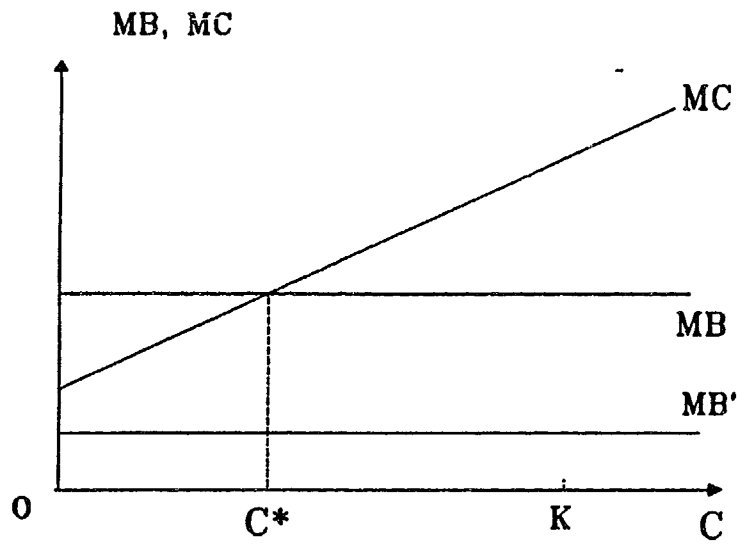


Figure 2 The Firm's Optimal Choice of Investment for Pollution Control

Figure 2 illustrates geometrically this policy implication. The marginal cost curve is linear in abatement investment (C) with a positive slope while the marginal benefit curve turns out to be horizontal since it does not change with the level of C. The firm's spending for environment protection will be zero if its marginal cost is greater than its marginal benefit--e.g. the marginal benefit curve is MB'. This case will happen if: (a) the pollution tax rate is very low; (b) the SEPA does not comply with the environmental law frequently; (c) the environmental protection expenses are not efficiently used; or (d) the firm's production pollutes the environment in a not-easy-to-monitor way. In this case, the SEPA's environmental policy does not affect the firm's behaviors in spending funds for environmental protection. This prompts corrections in either the firm's technical set-ups or the SEPA's inspection structure. The direction of policy changes, which affects the firm's behavior through its own optimization process, can be either increasing the marginal benefit or decreasing the

9. Their formal derivation is also provided in the Appendix.

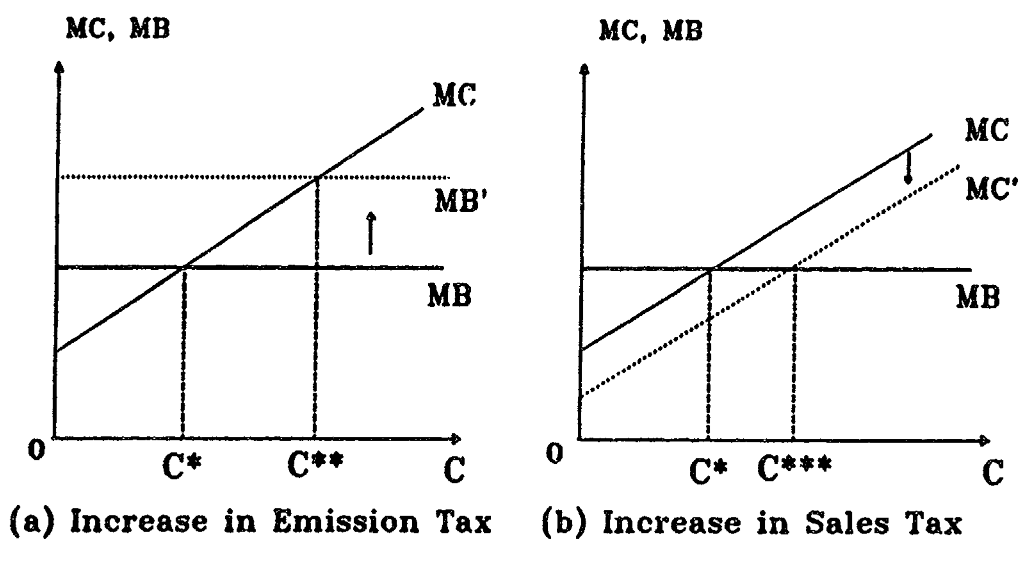
marginal cost of pollution control as they increase the marginal cost of polluting. These two options to change the behavior of the firm lead to the next six policy options:

<u>Policy Implication 2:</u> *Given the firm's technical parameters (production technology, pollution intensity and abatement efficiency), the effectiveness of the SEPA's environmental policy is determined by the <u>effective</u> pollution tax rate rather than by its <u>nominal</u> pollution tax rate. A low inspection rate discounts the firm's liability on pollution tax.*

<u>Policy Implication 3:</u> *If the SEPA has a <u>maximum pollution</u> tolerance level, the SEPA will have a <u>minimum pollution tax rate</u>. This rate should differ with the firms' production technology, pollution intensity and abatement efficiency.*

<u>Policy Implication 4:</u> *With a positive pollution tax rate, the more frequently the SEPA inspects the firm, the more the firm will allocate to pollution control.*

<u>Policy Implication 5:</u> *An increase in the VAT will also lead to short term reductions in pollution.*



<u>Figure 3</u> The Firm's Response to Policy Changes

Policy Implication 6: *If the structure of fines is proportional to the amount of pollution, subsidizing research projects on environmental protection or subsidies to the purchase of more efficient abatement technology by firms, would improve the incentive of firms to invest in abatement.*

Policy Implication 7: *Tax rates, inspection frequency and research subsidies can be used as substitutes to induce the firm to cut pollution.*

Figure 3 compares the effects of a sales tax and of a pollution tax on the decision to invest in abatement. This result is driven by the short term nature of the model and full employment assumption of the model does not say much about the ranking of the instruments--a firm could react by cutting capacity utilization. Once capital becomes variable the policymakers should not view the two types of taxes as equivalent. The pollution tax dominates as it clearly addresses the externality.

ii. The SEPA's perspective

The state government is assumed to emphasize its tax revenue which reflects employment, local output and regional development. It considers environmental quality as secondary to these macroeconomic objectives. Knowing the whole process of the firm's decision making, the SEPA decides an inspection frequency to monitor the firm's performance on environmental protection. Its optimal monitoring choice is determined by a comparison of its marginal costs and its marginal benefits of monitoring as shown in Figure 4 (ii).

The marginal cost consists of three elements: the marginal (and average) cost of conducting inspection, the marginal reduction of the value-added tax revenue, and the marginal tax loss due to shrinking of the pollution tax basis. The marginal benefit of inspection comes from two sources: the increase of pollution tax actually collected, and the savings of the otherwise-paid expected penalty to the federal government.

The trade-off the SEPA faces is that on one hand, a harsh monitoring scheme induces the firm to reduce its productive capital and its output level and thus decreases the SEPA's value-added tax revenue. It also reduces net revenue as monitoring costs increase. On the other hand, it may increase the SEPA's tax collection from pollution tax and avoid possible penalty to the federal government if the FEPA finds out that the SEPA does not monitor the firms. The importance of this cost depends on the federal inspection efforts.

If the pressure from the federal government is small--i.e. the FEPA ignores completely how well the SEPA does its job-- as is currently the case in Brazil, the SEPA's marginal cost of inspection will surpass the corresponding marginal benefit. This is represented in Figure 4 (i). It means that the SEPA should not spend any time monitoring the firms. At the other extreme, if the marginal cost of monitoring is very small, the SEPA should do a perfect monitoring job as shown by Figure 4 (iii).

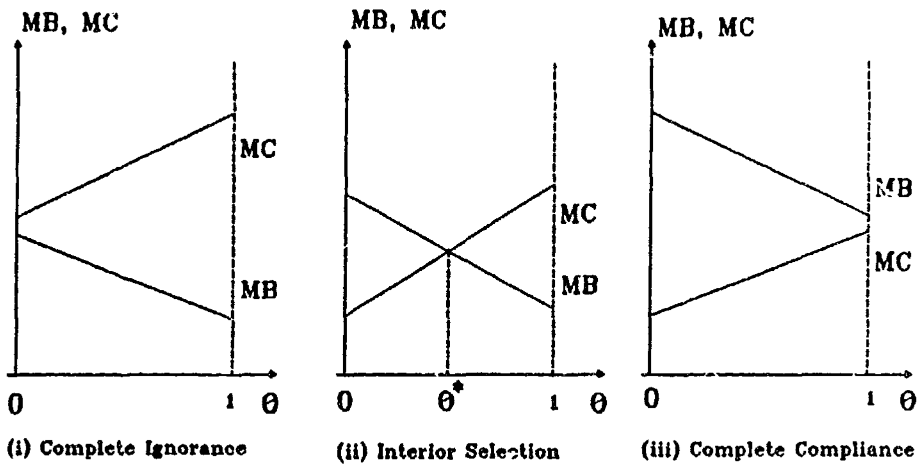
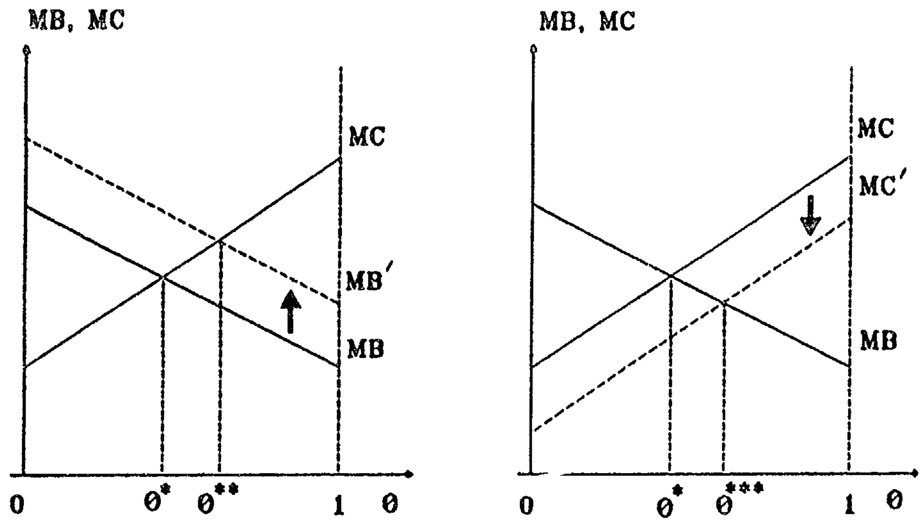


Figure 4: The SEPAs' Monitoring Choice

How the FEPA could react to this set of possible of outcomes, is summed up in the next three policy implications of the model and illustrated in Figure 5:

Policy Implication 8: *An increase in the federal penalty or inspection level will raise the SEPA incentive to comply with its obligations and increase its own monitoring frequency--thus reduce pollution.*

Policy Implication 9: *Subsidies to cut the states' monitoring costs would lead the SEPA's to monitor more frequently and would hence reduce pollution.*



(i) An increase in the penalty level or the federal authority's inspection frequency

(ii) A reduction in the regional authority'smonitoring cost

Figure 5: Impact of Changes in Federal Fines and Monitoring Costs on the SEPAs Policy Selection

Now consider the case in which the federal government has an upper bound for the level of pollution it is willing to live with. Just like a pollution ceiling had an effect on the optimal effective pollution tax rate for the states, a federal pollution ceiling has an impact on the optimal federal fine. More specifically:

<u>Policy Implication 10:</u> *If the FEPA has a maximum standard for the pollution intensity in the environment, it can define a set of appropriate penalty level and inspection rate such that its target on environment protection can be achieved through changes in the behavior of states and hence of firms.*

iii. The FEPA's perspective

The Federal government--represented by the FEPA-- wants to promote growth but also wants to keep pollution under control. The model allows to simulate various levels of distaste for pollution. This can be used to simulate the changes in the expected behavior of the FEPA that would result from changes in pressure intensity from the population or from organized lobbies. It relies on the SEPAs to ensure that the firms comply at least with the minimum federal environmental requirements. To ensure that the SEPAs do their job, it needs to inspect the states and may consider to somehow fine the poor performing states. The FEPA picks its monitoring rate by comparing its marginal costs of inspection to its marginal benefits.

The FEPA's marginal cost of monitoring is composed of (i) its marginal (and also average) cost of conducting monitoring, (ii) marginal utility loss from reduction of the firm's output, and (iii) the reduction of the expected penalty collection from the SEPA. The FEPA's marginal benefit includes the marginal utility from the reduction of pollution level and the marginal increase of the expected penalty collection due to its harsher monitoring. The understanding of the composition of the marginal cost and benefits leads to the last two--and rather obvious-- policy implications:

Policy Implication 11: *The more the FEPA dislikes pollution, the more often the FEPA will monitor the SEPA's performance and hence the lower pollution will be.*

Policy Implication 12: *Reducing the FEPA's inspection cost will contribute to alleviate environmental pollution.*

Therefore, a smaller inspection cost will reduce the FEPA's aggregate marginal cost of inspection and thus raise the FEPA's optimal inspection rate. In response to this federal policy change, the SEPA will adjust its monitoring frequency. Consequently, the firms' portfolio is altered and the pollution intensity level is reduced.

3. Numerical Policy Simulations for Brazil

This section presents numerical simulations illustrating the practical importance of some of the policy conclusions derived from the theoretical model. The simulations focus on sectoral data at firm level data are not available. They require data on sectoral capital stocks, outputs and an indicator of the pollution intensity. These data are not available for all sectors as discussed in the Appendix. The data available, however, allow a rough (OLS) estimate of the production function for a few sectors. This provides the basic technical parameters representing the efficiency of productive capital. The abatement rate of the pollution control investment can be selected exogenously to reflect its reduction efficiency. The policy parameters are the value-added tax rate, the pollution tax rate, the monitoring costs for the SEPA, the inspection costs for the FEPA, the federal penalty level and a coefficient reflecting the relative level of the federal government aversion to pollution.

The weakness of the data base implies that the specific numerical results obtained here are not robust enough to be able to make specific recommendations on policy decisions such as the optimal federal fine or inspection rate or on the optimal pollution tax or monitoring rate. The numerical results are however robust enough to illustrate the importance of some specific aspects of the design of pollution control policies such as the size of fines or of the pollution tax, the differences in monitoring and inspection requirements of dirty and clean industries or the potential role of subsidies to the firms or to the states.

The illustration focuses on the Printing and Publishing sector as a representative dirty industry and on the Food sector as a representative cleaner industry as shown by Table 1. For these two sectors, the coefficients of the production functions were statistically significant. They are likely to be somewhat outdated however as they are based on data for the seventies. For pollution intensity, we relied on series prepared by David Wheeler and his team in the Environmental Department of the World Bank. The series provide measures of toxicity per sector in the U.S. When applied to Brazilian production data, they provide an indicator of the absolute level of pollution generated by each sector in the sample.[10] The estimates suggest that Printing and Publishing is a much more polluting industry than the food industry per unit of capital. However while it is also much more polluting per unit of output, it is actually somewhat less polluting that the Food sector when production levels are accounted for. The Food industry is indeed much larger than the printing and publishing industry in the country. In absolute terms, both sectors are in the top 5 polluting sectors for the sample selected.

This section is organized as follows. It first presents a detailed discussion of the optimal inspection and monitoring policies for the two case studies. Next, focusing on the dirty industry, Printing and Publishing, it provides simulations of the importance of fines, VAT rates, pollution tax rates and abatement efficiency levels for the success of pollution control.

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10. The selection of the sample was based on the information available to estimate the capital stock. Only those sectors in the SITC categories for which capital stock could be estimated were retained.

Table 1: Ranking of Pollution Intensity for a Sample of Industries (1980)

Sector (SITC classification)	Pollution Intensity per unit of Capital	Absolute Pollution Level
Leather & Products	1	6
Plastic Products	2	2
Printing & Publishing	3	5
Other Paper Products	4	1
Drugs & Medicine	5	11
Non-Ferrous Metal	6	3
Furniture	7	9
Wood Product	8	7
Other Textile Products	9	8
Rubber Products	10	10
Transport Equipment	11	12
Food Products	12	4
Tobacco	13	14
Beverages	14	13

3.1 Comparing Optimal Policies for "Dirty" and "Clean" Industries

This section illustrates the differences in the optimal federal and state behavior in the treatment of clean and dirty industries. The abatement efficiency is supposed to be twice the value of pollution intensity ($\omega = 2\ \psi$ in the notation of the Annex) in each one of the sectors. This arbitrary choice does not affect the core of the results as will be clear by the end of this section. This means--from equation (4) in the Annex--, that to completely eliminate pollution in either sector, the maximum share of investment in pollution control in total capital should be 33.3%. In addition to the difference in terms of ψ, the sector differ in the productivity of capital and in the level of output. A summary comparison the results is provided in Table 2.

The discussion focuses on the impact of optimal inspection and monitoring policies on private investment in abatement, output, pollution and on federal and state revenue implications of pollution control. Most cases are normalized to the value taken by that variable when there is no federal inspection and no state monitoring.

The model is solved for each one the three agents. First, the utility of the federal government, a proxy for the economy's social welfare, is computed as a function of the SEPA's inspection of the firms. In the model, the inspection rate increases from 0% to 100%, stepping with 5%. Since the federal utility level varies with its degree of aversion, λ, the utility is calculated for three degrees of aversion to pollution: no aversion (λ=0), low aversion (λ= 0.1), high aversion (λ=1). For food, the optimal no aversion ($\lambda=0$), low aversion ($\lambda= 0.1$), high aversion ($\lambda=1$). For food, the optimal degree of federal inspection varies with λ from 10% to 100%. It reaches 100% for a high degree of aversion. For Printing and Publishing, it requires less than perfect inspection only when there is no aversion to pollution. This suggests that even at very low levels of aversion, the federal government should allocate more resources to inspecting the states' monitoring of dirty industries.

To every degree of federal inspection corresponds an optimal degree of state inspection. This optimal degree of inspection does not necessarily match the first best policy for the state. In fact, states revenue will be less when SEPA's choice of monitoring efforts is constrained by the federal leadership as shown by Table 2. For Food, it will be at least 10% less (167%/186%), for Printing & Publishing, it will be 48% less (75%/143%). In the case of the clean industry, the revenue from the pollution tax can however be sufficient to offset the loss from VAT revenue. Only when the FEPA is very averse to pollution will it lead to a lower revenue than without any monitoring. This is precisely why when the FEPA is very averse to pollution or when the industries are very dirty, federal inspection rates have to be perfect (100%). In addition, if the FEPA does not monitor the SEPAs, they will tend to monitor more frequently clean industries than dirty industries. The unconstrained optimum state monitoring is 45% for food but 40% for Printing and Publishing.

Similarly to every degree of state monitoring corresponds an optimal firm behavior which leads to a specific combination of output and pollution. This combination is in fact driven by the effective pollution tax rate. For a given nominal tax rate, a minimum level of state monitoring is required to ensure that the firms start investing in pollution control. It is 44.9% for the clean industry and 3.4% for the dirty industry. This is due to the much larger revenue payoff of a control of the dirty sector. It also reflects the fact the optimal federal fine on states for failing to monitor firms is larger the dirtier the industry.[11]

The process just described is known to the FEPA. Hence, based on the impact of its inspection efforts on the states and on the firms' behavior, the FEPA picks the inspection rate that will lead to a combination of pollution and output that maximizes the social welfare function. The optimal degree of firms monitoring by the states is the degree at which federal utility is maximized. Once more it depends on the federal aversion to pollution. The stronger the federal aversion to pollution and the dirtier the industry, the larger the monitoring effort required from the state. The state's

11. The optimal federal fine is defined as the fine level such that if federal inspection is perfect, it will induce a perfect monitoring of firms by the states.

position reflects a combination of the impact of federal fines, and net revenue from states VATs and pollution taxes. The share of capital allocated to pollution control by the firm is then based on the degree of state monitoring and the pollution tax rate. These influence the output level that will maximize profits. The output level and the abatement efficiency of capital then determine the new pollution level.

In addition to the impact on profits, pollution control reforms would also change states' revenue and have implications for the federal budget. The implications on the state's budget depend on VAT revenue, net pollution tax revenue and the fine levels. VAT revenue are offset by the increased net revenue from a pollution tax. Revenue needs to be considered on a net basis as monitoring is not free. There is however no reliable data on monitoring cost at this stage and these are not considered important in the simulations presented above. We define an optimal penalty level instead. Finally, the effective fine set by the FEPA also contributes to determine the states' choice. It reflects both the level of the fine and the monitoring efforts discussed above. In general, the level of the optimal fine will also depend on the polluting nature of the sector. Assuming fixed common standards for all industries, the dirtier the industry, the larger the fines should be. This holds even if in absolute terms the Food sector generates more pollution than the Printing and Publishing sector. In budgetary terms, it means that if the federal government is even mildy averse to pollution, it will need to accept a deficit in its monitoring activities--i.e. pollution control has to be subsidized. [12]

In sum, Table 2 shows that the federal government should focus its inspection efforts on the quality of State's monitoring of dirty industries. This reflects the importance of federal aversion to pollution. But more importantly, it reflects the fact that to maximize net revenue and minimize the output losses implied by stronger monitoring, without federal supervision, the SEPAs are more likely to focus on large clean industries than on dirty industries because of the combined VAT and pollution revenue is higher for those industries. To achieve this objective, the federal government may need to allocate resources to assume the cost implied by inspection as for dirty industries and/or high pollution aversion, inspection cost are generally larger than fines revenue.

12. The federal monitoring cost picked in the model is arbitrarily set at 10% of the value of the optimal federal fine.

Table 2: Comparing Optimal Policies for Dirty and Clean Industries
(Policies that Maximize the Federal Welfare)

	Food (The Clean Industry)	Printing & Publishing (The Dirty Industry)
Optimal Federal Inspection Rate for Various Degree of Aversion to Pollution (λ)		
no aversion	10%	15%
low aversion	45%	100%
high aversion	100%	100%
Optimal State Monitoring Rate		
With Federal Intervention		
no federal aversion	52%	100%
low federal aversion	71%	100%
high federal aversion	100%	100%
With no Federal Intervention	45%	40%
Investment in Pollution Control		
with Federal Intervention and		
no aversion	5.5%	19.7%
low aversion	14.3%	33.2%
high aversion	30.0%	33.2%
with no Federal Intervention	0%	12.6%
Minimum State Monitoring Required for a Non-zero Investment in Pollution Control	44.9%	3.4%
Pollution Level (as % of current)		
with Federal Intervention and		
no aversion	88%	49%
low aversion	58%	1%
high aversion	10%	1%
with no Federal Intervention	100%	62%
Value Added (as % of current)		
with Federal Intervention and		
no aversion	97%	93%
low aversion	88%	75%
high aversion	68%	75%
with no Federal Intervention	100%	96%
State Net Revenue (as % of current VAT revenue)		
with Federal Intervention and		
no aversion	167%	75%
low aversion	101%	75%
high aversion	87%	75%
with no Federal Intervention	186%	143%
Federal Net Revenue (as % of current VAT revenue)		
with Federal intervention and		
no aversion	14%	15%
low aversion	32%	-24%
high aversion	-37%	-24%
with no Federal Intervention	0%	0%

3.2 Implications of Reforms for the Printing and Publishing Sector

3.2.1 Which Government Level Should Try to Improve Abatement Efficiency?

Abatement efficiency is a critical variable for the success of pollution control policies. Improvements in abatement efficiency could be a very successful policy as illustrated by Table 3. A tenfold increase in abatement efficiency could reduce pollution by 23% more while reducing output, as compared to a situation without pollution control, by only 3% instead of 21%. This stems from the fact that the maximum share of capital to be allocated to pollution control is cut from 67% to 17%. Social welfare will be maximized at levels of investment in abatement somewhat lower: 28% for an ω of 0.5 and 11% for an ω of 5.

These results suggest that the government should consider subsidies to the research in this area or assist the firms in acquiring more efficient abatement technology. It is unlikely, however, that the states will be willing to make the effort. Table 3 shows that, assuming that states only care about revenue, states would be better off with low efficiency abatement technology. A tenfold improvement in technology would cut the combined net VAT and pollution tax revenue to just over a third of what it would be without the improvement. In fact, the new revenue would be even somewhat lower than without any investment in abatement. This revenue erosion mostly reflects the reduction in pollution and in the optimal pollution tax rates.[13] If state monitoring costs were also important, they would further erode revenue as the optimal monitoring rate implied by the FEPA's position is more than twice the original requirement.

In sum, if a subsidy could contribute to the improvement of abatement efficiency available to firms, it should be considered by the Federal government rather than by the states. It should, however, compare the degree of improvement in technology to the cost of the subsidy. Doubling abatement efficiency would not achieve much in absolute reduction in pollution. But if the cost of a subsidy represents less than 8% of the current value added, it may be worth to consider it because doubling the original abatement efficiency would increase output by 8%.[14]

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13. The optimal pollution tax rate is the rate required to cut pollution to 0 when the SEPAs are monitoring perfectly (100%).

14. An additional, maybe more audacious, conclusion from the same data would recommend an approach to the selection of firms to monitor within a specific sector. Assume that the technical coefficients--i.e. the marginal productivity of capital--for all the firms in the sector are the same. Assume also that firms only vary in terms of pollution intensity. Then Table 3 implies that the firms for which the increase in abatement efficiency can be the largest should be more likely to be monitored because state monitoring requirements increase with abatement efficiency. In practical terms, this means that the SEPAs should keep firms with older capital in closer check than firms with more recent capital if it is likely to be less polluting. It also implies that if a subsidy is to be allocated for investment, they should go to the older firms first if they have the same marginal productivity of capital as the more recent firms.

Table 3: Impact of Changes in Abatement Efficiency Rates

	Abatement Efficiency Rate as % of Pollution/capital (ω as % of ψ)			
	50%	100%	200%	500%
FEDERAL				
Federal Inspection Required (for low pollution aversion; λ=.1)	100%	100%	100%	100%
Federal Penalty Level Required as % of original VAT revenue	30.7%	30.7%	30.7%	30.7%
Net Federal Fine Revenue as % of original VAT revenue (for a constant fine)	13.5%	13.3%	11.8%	5.8%
STATE				
Resulting State Monitoring	46%	48%	51%	71%
Minimum Monitoring required for firm to invest in control	1.7%	2.3%	3.4%	6.6%
Net State Revenue as % of original VAT revenue	251%	179%	128%	98%
Nominal Pollution Tax required to reduce pollution to 0 with perfect SEPA monitoring	10.4cts/lb	5.9cts/lb	2.6cts/lb	.7cts/lb
FIRM (at the level of monitoring implied by the federal attitude)				
Investment in Pollution Control as % of total capital	28%	24%	16%	11%
Max. investment in control as a % of total capital	67%	50%	33%	17%
Pollution Level as % of original	55%	55%	51%	32%
Value added as % of original	79%	87%	93%	97%

3.2.2. Do States React to Changes in Federal Fines?

The previous set of simulations established that for dirty industries, the federal government should monitor the states perfectly when the fines are set at their optimal level. But what if the fines cannot be set at the optimal level? This implies that the effective fine, considering both inspection and fine levels, will also be sub-optimal. This will reduce the states' incentive to adopt the monitoring rate that will maximize social welfare. Since it is generally unrealistic to assume that fines will be optimal, it is useful to see the extent to which the fine level matters.[15] A set of simulations shows how changes in the level of federal fines, expressed as a percentage of the VAT revenue without pollution control, affects the main variables of the economy.

First of all, it is clear that if the fine is trivial, the FEPA might as well not monitor the states. In other words, if the federal government was to consider fining states as a policy instrument to improve the environment, it has to be willing to pay for this activity and include into its budgetary requests even if it is only somewhat averse to pollution.

Assuming that the fine level is directly linked to the cost of monitoring--say 10 times for the purpose of simulations--, inspections will generally cost more than they will yield. The larger the cost, the larger the optimal fine to achieve zero pollution, but also the lower the effective fine as the threat increases and state compliance improves. Hence the larger the federal deficit from its inspection operations. Fines do not have to be related to cost and if this were not the case, the FEPA may end losing less that suggested by Table 4. But it is likely to lose when state compliance improves as a result of perfect federal inspections. The social welfare payoffs of the changing combination of pollution and output increase with the fines levels. But the states end up worse off as the fines level increase. The deterioration is not due to an increase in the effective costs of penalties but to the reduction in net revenue. When federal fines are optimal, even pollution tax revenue is not enough to offset the loss from value added tax revenue and states net revenue drop to 94% of their original value. The absence of fines does not mean however, that the states will not do anything in terms of pollution control. In fact, as the next section will illustrate more clearly, the mere existence of the pollution tax, even at a modest rate, is sufficient to lead to an improvement in the environment. For the specific case illustrated by Table 4, even when the federal government does not inspect the states, state revenue is 144% of what it would have been without the pollution tax and pollution is only 57% of its original level.

From a practical aspect, fines can take several form. One form that it could take in Brazil would be a reduction in Federal Transfers. This is particularly interesting in the context of pollution as the Federal government is cofinancing various operations with the states. This cofinancing often takes the form of a matching grant. Introducing

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15. From an administrative point of view, the fine will have to be unique or at worst be differentiated according the pollution intensity of capital of the sector and to pollution level. To derive the corresponding minimum rate of inspection required, take equation (24), set the state monitoring level to the minimum required to have firms invest in abatement and the fine level selected, then solve for eta.

conditionality for the disbursement of the grant could be related to the monitoring efforts of the states. The reduction in the grant amount for non-compliance would be equivalent to a fine. Now, it is politically unrealistic to assume that the fine could wipe out state revenue or even anything close to half these revenue. But the magnitude of the costs of some of the projects--think of Guanabara in Rio de Janeiro or Rio Tiete in Sao Paulo-- is so impressive, that the federal grant component could easily reach a third of the tax revenue of a state for any given year. In those cases, fines would be in the range defined by the second and third column of the Table. However, the improvements in pollution levels achieved by the fine are not significantly higher than those achieved from the pollution tax only.

Table 4: Impact of Changes in the Federal Fine on the States

	Federal Fine as % of original States' VAT Revenue				
	0.0%	15.3%	30.7%	153.3%	246.1%
Utility Maximizing Inspection level for low pollution aversion	0.0%	100%	100%	100%	100%
Social Welfare (% of Case with Fine=0)	100%	163%	223%	592%	746%
Net Federal Fine Revenue as % of original VAT revenue	0.0%	6.4%	11.8%	16.9%	-24.5%
STATE					
Resulting State Monitoring	44%	48%	51%	79%	100%
Net State Revenue as % of original VAT revenue	144%	135%	128%	85%	92%
Nominal Pollution Tax required to cut pollution to 0 w/ perfect SEPA monitoring	2.6cts/lb	2.6cts/lb	2.6cts/lb	2.6cts/lb	2.6cts/lb
FIRM					
Investment in Abatement (% of total capital)	14%	15%	16%	26%	33%
Pollution (% of original)	57%	55%	51%	32%	5%
Production (% of original)	95%	94%	93%	84%	75%

In sum, fines are necessary to establish the credibility of the federal government penalization of states that do not assume their monitoring role with enough conviction. However, to cut the pollution levels significantly below the reduction achieved by the pollution tax, fines may have to reach levels politically unrealistic. Their value is hence somewhat limited and mostly complementary to the impact of the introduction of a pollution tax at the state level.

3.2.3 Why do Pollution Taxes Matter So Much to All Levels of Governments?

The discussion has so far shown that the pollution tax is a crucial component of the success of decentralized pollution control. But previous results have shown that the optimal pollution tax will vary across sectors. For instance, the larger the degree of abatement efficiency available to the firms, the lower the required optimal tax rate.[16] The optimal rate also varies with the pollution intensity of the sector. The cleaner the industry, the larger the "legal " tax rate required.[17] For instance, the optimal federal inspection level would lead to an optimal pollution tax rate in the Food sector about 4 times larger than in the Printing and Publishing sector. This is driven by the lower minimum monitoring requirement for the cleaner industry. But since in practice the pollution tax rate is likely to be uniform, it is useful to see what happens when the rate is not optimal. This is illustrated by Table 5.[18]

The most interesting result of Table 5 is that, for a given constant federal fine level equivalent to about 15% of VAT revenue, the optimal inspection rate for the federal government is 0 for very low pollution tax rates. This is because the FEPA knows that to maximize revenue, the states would have to monitor perfectly. This

16. Relying on the interpretation of abatement efficiency given in footnote 21. It suggest that the older the capital stock, the larger the abatement efficiency is likely to be to have the firm reach levels of emission per unit of capital comparable to firms relying on newer technology. If this interpretation holds, it implies that the older firms should be taxed less that the newer firms. This means that when firms have to make new investment decisions, they'd better consider the fact that they will be more penalized that in the past for not being up to standards with the latest development in pollution reduction built in capital.

17. To get this optimal tax rate, take equation (11), set theta=100% and P=0 and then solve for the pollution tax. Remember that the firm is influence by the effective tax rate which corresponds to the nominal tax rate weighted by the degree of monitoring. When monitoring is perfect, the effective tax rate is equal to the statutory tax rate.

18. The results are computed for an abatement efficiency of 2 and a Federal Fine level of 15.3% the original sales tax revenue.

results obtains because monitoring costs are assumed to be small. Larger costs would qualify these conclusions.[19]

These results however also give food for thoughts if the federal government is willing to consider subsidies of the monitoring activities. Table 5 suggests that, for a given level of sales tax revenue, as long as monitoring costs do not offset the revenue from pollution taxes, the states will have an incentive to monitor to capture the potential pollution tax revenue. While this is not addressed explicitly in this version of the model, this implies that the federal government should compare the costs of inspecting the states against the cost of subsidizing monitoring by the states.

Table 5: Importance of Pollution Taxes for Pollution Control

	Pollution Tax Rate (in cts/lb)			
	2.63	0.10	1.00	10
Utility Maximizing Federal Inspection level for low pollution aversion	100%	0%	0%	100%
Net Federal Monitoring Revenue as % of state revenue)	6.4%	0%	0%	12%
STATE				
Federally mandated State Monitoring	48%	100%	100%	11.3%
Minimum monitoring required for firms to invest in abatement	3.4%	89.2%	8.9%	0.9%
Net State revenue as % of original VAT revenue	135%	107%	143%	127%
FIRM (at the level of monitoring implied by the federal attitude)				
Investment in Pollution Control as % of total capital	15%	0.14%	11.88%	11.89%
Pollution Level as % of original	55%	99.58%	64.37%	56.72%
Value added as % of original	94%	99.99%	96.35%	94.78%

19. This will be addressed in a follow-up paper which will include a discussion of alternative modes of financing of these costs and their incidence on the federal and state budgets.

Table 5 also shows that leaving the selection of the pollution tax rate to the state may not be in the best interest of the environment. Setting the tax at 1 cts/ lb of pollutant for instance would lead the state to monitor perfectly but would not provide the incentive for the firm to curb pollution as much as it could. The firms will invest less in pollution control than under an optimal tax of 2.6cts/lb. The reason why there is a risk to leave the choice of the tax rate to the state is that by choosing a low rate, the state can collect more revenue than by choosing the optimal tax rate while still complying with the 100% monitoring requirement of the federal government. This leads to more sales tax revenue for the state but also to higher pollution levels because a lower than optimal effective tax rate is equivalent to a lower than required incentive for firms to invest sufficiently in pollution control. In other words, the marginal benefit of investment in abatement in terms of reduced pollution tax liability is lower than the marginal cost driven by the reduction in value added and hence profits.

There is however an additional important consideration for the design of the pollution tax. It is unlikely that the federal government will be able to set the tax at its optimal level for every sector. In general, the pollution tax should be a single flat rate tax to maintain it manageable. The effective tax rate will be adjusted by diversifying the monitoring effort. As mentioned earlier, this monitoring effort can be oriented by the federal inspection rate. The process however depends on the statutory tax rate defined in the law. What happens to those sectors for which the legal rate is higher than the optimal tax rate? Setting the tax rate too high as compared to the optimal may also cut the SEPA's incentive to perform well a monitor of the firms as shown by the last column of Table 5. But more importantly it cuts so much into profits that it reduces both the tax base for the VAT and for the pollution tax.

Take the case of the dirty industry when the federal fine is set at about 15% of the state revenue level and the abatement efficiency is twice the pollution intensity. The optimal pollution tax is then 2.63cts/lb. The revenue from the pollution tax increases very quickly with the monitoring rate but then starts declining when the monitoring rate reaches 50%. Total revenue starts declining when monitoring is around 40%. However, if the pollution tax is 10cts/lb, both pollution tax and total revenue starts declining when monitoring rate reaches 10%. The only cases in the simulations discussed so far where this phenomenon is not observed was when the pollution taxes were very low. The peak pollution tax revenue was then reached for 100% SEPA monitoring of firms. When this "Laffer curve" of pollution tax revenue is observed, it is due to the increase in investment in abatement that results from increased monitoring. While the Federal government may be satisfied by the existence of such a curve as it shows that the pollution tax base is shrinking fast, the states may not be as enthusiastic as their VAT base is shrinking and is not compensated by an increase in the pollution tax base. In fact, when the pollution tax rate is too high, the state never has an incentive to do more than what the Federal government wants it to do. Monitoring more than required cuts its revenue and may end up closing business as profits may turn negative at excessive tax rates. This observation contributes to justify the need for federal inspection. This last point is crucial because the dirtier an industry, the lower the required legal tax rate (as monitoring will be large), so the more likely that any the legal tax decided is likely to be excessive. In practice, it could also mean that the firm will start replacing investment in abatement by reduction in output as a mean of cutting pollution and hence the pollution tax base. In other words, the higher the tax rate, the more likely dirty firms are likely to drop out of the market.

The firm's switch from investment in abatement to plain reduction in output is however very slow. To be able to achieve a significant change in the firm's behavior as compared to the optimal tax rate, the statutory rate had to be set at almost five time the optimal rate. This is because the elasticity of most of the important variables such as value added, investment in pollution control and pollution level with respect to the pollution tax rate are much larger at low levels of monitoring that at levels that go beyond the optimal rate as shown by Table 6. In other words, the tax starts working very fast on the firms' and states' behavior and then its effect starts to decline as illustrated by the last column of Table 6. It shows that the elasticity of the pollution tax revenue with respect to the effective tax rate changes sign as the effective tax rate reaches 50%.[20] In practice, this is why penalties currently applied by Brazil's SEPA's are so successful but not quite enough. Indeed, most states rely on fines to penalize firms for non compliance. These fines work like pollution taxes in many states. Their level changes with the level of pollution observed during the random monitoring of the firm. In sum, it means that the state governments are in the right direction but they are not going far enough. They could raise much more revenue by increasing monitoring efforts and at the same time achieve improvements in the environment. Their behavior is driven by the mistaken belief that stronger effective tax rates, reflecting

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20. This holds for the assumptions built in the Table which represent the optimal situation for a fine level of 15% of VAT revenue and abatement efficiency of 2.

higher fines or better enforcement would lead to less tax revenue. In fact, as shown by Table 5, they are more likely to err by setting the effective rate too low than by setting it too high.

A last important aspect relating to the pollution tax is also provided by Table 6. It shows how fast the pollution tax works. While its stronger impact on investment in abatement is at low effective tax rates, the major impact on value added and on pollution intensity is at high effective tax rate. This also makes the case for a combination of monitoring and statutory tax rates that is not too low if the tax is to have more than just a revenue effect but is also expected to improvement the environment.

Table 6: Elasticity of the Main Variables with respect to a 1% increase in the Effective Pollution Tax Rate

Monitoring Rate	Investment in Abatement	Value Added	Pollution Intensity	Pollution Tax Liability
0%	0	0	0	0
10%	1.51	-0.01	-0.11	0.89
20%	1.20	-0.02	-0.25	0.75
30%	1.13	-0.05	-0.43	0.57
40%	1.09	-0.08	-0.66	0.34
50%	1.07	-0.14	-0.99	0.01
60%	1.06	-0.20	-1.48	-0.48
70%	1.05	-0.28	-2.30	-1.30
80%	1.04	-0.39	-3.91	-2.91
90%	1.04	-0.52	-8.60	-7.60
100%	1.03	-0.68	-216.38	-215.38

To sum up, the discussion so far has demonstrated the critical importance of the pollution tax to the success of pollution management in a decentralized economy such as Brazil. It will however be impossible to set the rate at an optimal rate for all sectors and hence a flat rate will be required. The states will have to adjust their monitoring rate across sectors to differentiate the effective tax rate. While setting the rate too high may be preferable to setting it low, it may be important to recognize the political economy aspects of the tax. Brazil's firms are already facing a large set of tax instruments and adding a new one now may not be feasible. One approach would be to simply systematize the use of fines and to design it as a predictable source of revenue for the states, thereby increasing its value as a complement to the VAT revenue and the incentive of states to improve monitoring to ensure collection of revenue from that sources. Even a sub-optimal a tax rate could achieve a significant contribution to pollution reduction in many of the most polluting sectors.

4. Policy Lessons For Brazil

The key message of the paper is that the interactive system that characterizes the multiple levels of decision makers in Brazil's institutional structure for environmental protection can be incentive-compatible, as well as financially sustainable. However, this requires that instruments be used and assigned appropriately across government levels.

The model presented highly simplifies many of the issues of concern to policymakers in Brazil.[21] Hence, it does not provide very specific recommendations such as what the actual optimal tax rate should be if a pollution tax were to be adopted. The model accounts however for most core institutional aspects of pollution management in Brazil and hence leads to some suggestions for reforms in pollution management that can result in improvements in policy implementation and benefit both the states and the federal government. Up to now:

i. IBAMA (Brazil's FEPA) has generally not been very enthusiastic about checking how well the states are performing their Constitutional assignment as monitors of the environment. Furthermore, IBAMA has not really relied on any systematic fine system to induce improvements in poor performing states. On occasions, federal matching grants for states construction projects have been overruled but the lack of transparency of the current system does not allow to suggest that this was related to the quality of states pollution control policies;

ii. States have not been very keen on IBAMA (the Brazilian FEPA) checking what they are doing. They have been using fines as the equivalent of

21. For instance, we did not explicitly model: (a) interrgional externalities; (b) interregional tax competition; (b) optimal subsidies for pollution control; and (d) repetition of the game.

pollution taxes but not nearly as much as they could have to maximize revenue or should have to improve the quality of the environment. This reflected their fear of having firms closing their doors or the fear of losing sales tax revenue as a result of excessive pressure on the firms. They have also been very unpredictable in their relation with the firms;

iii. The firms have used, very rationally, the extreme leniency shown by the states and the lack of involvement of IBAMA, to minimize their efforts to reduce pollution. The most polluting firms have invested when public pressure was strong enough to force them to do so but without monitoring from the SEPA they are unlikely to have much incentive to minimize pollution.

To cope with these facts, the paper provides two main policy recommendations. The first is that the federal government needs to keep a closer eye on how firms deal with the dirty industries relative to the clean industries. When states care mostly about revenue, they will tend to spend more resources focusing on less polluting industries. IBAMA can rely on a combination of 3 main instruments: inspection rates, fine levels and subsidies to firms for abatement or states for monitoring. If fines are high enough the federal inspection effort required should not be excessive in terms of budget requirements. In general, as realistic fine levels are unlikely to lead to full state compliance with monitoring requirements, the net revenue from increased inspection should be positive.[22]

The second recommendation is an endorsement of the pollution tax considered by many states as an instrument to both reduce pollution and finance pollution control policies. The tax should clearly be a state tax rather than a federal tax if the states have to have a strong incentive to perform their Constitutional assignment. To avoid possible strategic behavior by states inconsistent with federal objectives, the federal government should probably set the tax rate. The rate should not be set too low because low rates favor dirty or old industries for which large potential improvements in abatement are possible. The rate could be a minimum that states could reinforce it if

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22. This inspection role could actually be assigned to the private sector and cost recovery for their services should be one of the component of the design of the fine.

they felt it was a way for them to compensate for lack of resources to ensure the monitoring requirements imposed by the federal government. Whatever the actual design of the tax, its implementation will improve the environment even if the FEPA does not inspect the states. There may be sunk costs required to acquire the monitoring instruments and to set up the infrastructure and these may be cofinanced with the federal government. Except for those capital costs, the pollution tax could lead to self sustained industrial pollution control as its revenue potential is generally sufficient to increase states' net revenue even when losses in VAT revenue are accounted for. In many of the Southern states such as Parana, Sao Paulo and Rio de Janeiro, pollution taxes are being considered to curb industrial pollution.[23] It is unfortunate that many of the poorer states are not considering that instrument. However small the industrial sector, the pollution tax will help. It could be paid by the agricultural sector but also by state water companies for instance, in many states they are responsible, directly or not, for a very large share of water pollution.

In addition to these two main recommendations, the paper also makes the case for subsidies to improvements in the degree of abatement efficiency relied upon by firms as a way to reduce the short term growth costs of pollution control. The paper points to some of the limitation of pollution taxes in the "real world" as compared to the economist's world. A single flat rate across sectors is about the only administratively realistic approach to the tax. Its adjustment through monitoring to achieve the effective tax rate is essentially impossible. The directions for differentiation of monitoring efforts are however very clear. As expected, the less efficient the firm's abatement technology and the more polluting the firms, the stronger the monitoring effort should be, for a given statutory tax rate.

23. Misunderstandings about some of the implications of pollution taxes on state revenue or on output levels may explain why in Rio de Janeiro, for instance, the pollution tax has been proposed various times by the SEPA with a clear design but has never benefitted from the complementary regulation required for its implementation.

ANNEX

This annex provides a formal presentation of the model described in section 2. It reproduces the hierarchical decision making structure of Brazil's pollution control management. To simplify the presentation, we focus on the vertical behavioral relationship between the FEPA, a representative SEPA and a representative firm.

1. The Firm's Problem

The firm has a fixed capital stock in the short-run, K, which can be used either to produce an output or to abate pollution generated in the production process. For simplicity in deriving our policy implications, we assume that the firm has a well-behaved quadratic production function, which serves as a second order approximation to any twice differentiable production functions at least in the equilibrium neighborhood[24]. So, we can write the firm's value-added production function as

$$Y = \alpha\,(K-C)^2 + \beta\,(K-C) + \gamma \qquad \alpha < 0,\ \beta > 0 \tag{1}$$

where Y is the output level, C ($0 \leq C \leq K$) is the firm's investment for environmental protection, α, β and γ are technical coefficients reflecting the efficiency of the productive capital. Here, the inequality $\alpha < 0$ ensures the concavity of the production function, and $\beta > -2\alpha K$ is a necessary condition for the marginal product of the productive capital being positive[25]. Contributions from other productive factors, such as labor and technology, are embodied in γ, in addition to α and β.

The pollution intensity associated with the above production scheme is assumed to be presented by a pollution function

$$P = p(Y,\ C), \qquad p_1 > 0,\ p_2 < 0 \tag{2}$$

24. Using Cobb-Douglas production function or other CES production functions will generate the identical qualitative results but creates discontinuity in players' reactions.

25. The marginal product of the productive capital is

$$\frac{dY}{d(K-C)} = 2\alpha\,(K-C) + \beta$$

A positive $dY/d(K-c)$ requires that $2\alpha(K-C)+\beta > 0$ holds for all possible values of C. Especially, when the firm does not control its pollution at all, i.e., $C = 0$, we shall have $\beta > -2\alpha K$.

where P is the index for pollution intensity. p_1 and p_2 are partial derivatives of P with respect to Y and C, respectively. Hence, (2) implies that the pollution intensity in the environment will increase with the output level but decrease if more funds are spent for environmental protection. In many countries, including Brazil, the SEPA cannot measure polluting emissions directly and hence it is difficult to determine the base for a pollution tax. An alternative is to focus on the pollution-generating factors in production. In our model, the productive capital K - C is the only easily measurable polluting factor. [26] With this constraint of measurement, we can simplify the firm's pollution function as

$$P = \psi (K - C) - \omega C \qquad \psi > 0, \quad \omega > 0 \tag{3}$$

where ψ is the pollution rate of the productive capital and ω is the abatement rate for the environment protection investment. The linear approximation (3) of the pollution function (2) is acceptable in the neighborhood of the firm's optimal choice of C. Of course in practice, the pollution rate per unit of capital varies from sector to sector and within a sector, it varies with the age of the capital stock. More recent equipment is likely to have lower pollution rates.[27] The data required at the firm level are however generally not readily available and the average pollution intensity of the sector will be used instead in the simulations.[28]

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26. In practice, many SEPAs in Brazil are starting to acquire an increasing knowledge of the pollution intensity of the capital stock. It is not only derived from current inspection practices but also from the requirement that an environmental impact assessment be presented before major new investments are authorized.

27. Generally, the reduction in pollution due to a specific pollution abatement device can be derived from engineering data. Denote this rate of abatement by a. The following relationship between ω and a, then holds for any specific combination of K and C:

$$\frac{\psi (K - C_d) - \omega C_d}{\psi K} = 1 - a$$

where C_d is the market price of the device. So the abatement rate can be expressed in terms of the pollution rate, the device abatement rate and the cost of the abatement device, i.e.,

$$\omega = \psi \left[a \frac{K}{C_d} - 1 \right]$$

28. The approximation for pollution intensity used in the simulation is based on David Wheeler's series.

In more general terms, equation (3) says that in addition to the obvious reduction in pollution due to the reduction in output, reflecting a lower productive capital stock, pollution will decline as a function of the abatement technology adopted. Take the case of water pollution due to heavy metals for instance. The share of capital C would represent a treatment station that would result in a reduction in pollution levels per unit of capital used in production. Reduction of pollution will however vary with technology. An anaerobic filter would only achieve a 50% reduction while chemical treatment would achieve a 90% reduction.

From (3), we know that to completely eliminate the pollution effect of production, the firm has to invest $C = \psi K/(\omega+\psi)$, which serves as a ceiling level of investment for pollution control. In other words, the ratio of capital stock allocated for environmental protection over the total capital stock has to satisfy the following constraint,

$$0 \le \frac{C}{K} \le \frac{\psi}{\psi + \omega} \le 1 \tag{4}$$

This means that a "dirty" industry with a low abatement efficiency will have a relatively high ceiling level for environmental protection investment.

Now consider the determinants of the firm's profits. Firm profits are affected by two taxes. The first is a state value-added tax at rate t_y. The second is a new pollution tax that an increasing number of states are trying to introduce. Assume it is based on emissions at rate t_p and that it can only be levied if the SEPA checks the environmental quality. In this case, the firm's profit function can be written as

$$\begin{aligned} \pi(C; K) &= (1 - t_y)\,Y - rk - \theta\, t_p P \\ &= (1-t_y)\,[\alpha(K-C)^2+\beta(K-C)+\gamma] - rK - \theta t_p[\psi(K-C)-\omega C] \end{aligned} \tag{5}$$

where θ is the probability that the SEPA monitors a specific firm in the sector. In practice, since this is a short term model, once a firm has been inspected, the SEPA knows what proportion of the capital stock is allocated to pollution control and can collect the pollution tax until the firm can prove that it has changed its C. Some of the information could be collected in the process of the environmental impact assessment (EIA). The EIA, when implemented correctly, provides a significant volume of data on the nature and intensity of the polluting activity of a firm. This information could be--and is, for some sectors and in some states in Brazil-- at the core of the information available to decide which firms to monitor. If all the firms are checked in a year or if all firms need to go through an EIA, the probability is 1. Another interpretation could be that a probability of 1 means that the sector is monitored once a week--but never on the same day. Any reduction in the frequency of visits to the firm cuts the probability. For any given capital stock K, r is the market-determined rent for capital and rK is a fixed cost the firm has to pay to hold K. In the short-run, we assume that r and K are both stable with respect to the firm's decision on how much to spend to abate the pollution. In other words, the firm can respond to the SEPA's policy faster than the capital stock and rent can change.

For any given θ and K, we can derive the first order condition for the firm's profit maximization problem, where the first derivative of $\pi(C;K)$ with respect to C is

$$\frac{d\pi(C;K)}{dC} = -(1-t_y)\,[2\alpha(K-C)+\beta] + \theta\, t_p(\psi+\omega) \tag{6}$$

The second order condition for maximization

$$\frac{d^2\pi(C;K)}{dC^2} = 2\alpha(1-t_y) < 0 \tag{7}$$

is satisfied for all choices of C, since $\alpha < 0$ and $t_y < 1$. Therefore, the firm's profit is maximized when its selection of C satisfies the following equation

$$(1-t_y)\,[2\alpha(K-C)+\beta] = \theta t_p(\psi+\omega) \tag{8}$$

The intuition behind (8) is that the firm chooses C to balance its marginal gain of investing for environmental protection and its marginal cost of doing so. At the margin where the optimal C is set, one dollar investment in controlling pollution will save the firm pollution tax by $\theta t_p(\psi+\omega)$ while cost the firm $(1-t_y)[2\alpha(K-C)+\beta]$ in terms of after-tax sales revenue. If the pollution tax is zero, equation (6) and the assumption of concavity of the production function shows that the firm will maximize profits by ignoring pollution control altogether (C=0).

Policy Implication 1:

If the marginal cost of pollution abatement, as presented on the left hand side of (8), is greater than the marginal benefit of abating pollution, as presented on the right hand side of (8), then the firm will reduce its investment for pollution control. Especially, when $\theta t_p(\psi+\omega) < (1-t_y)(2\alpha K+\beta)$, the firm will feel it rational to completely ignore its environmental responsibility.

Policy implication 2

Given the firm's technical parameters, α, β, ψ and ω, the effectiveness of the SEPA's environmental policy is determined by the effective pollution tax rate θt_p instead of its nominal pollution tax rate t_p. A low inspection rate discounts the firm's liability on pollution tax.

With the assumption that[29] $\theta t_p(\psi+\omega) \geq (1-t_y)(2\alpha K+\beta)$, we can solve the firm's optimal selection of C, from equation (8), as a function of all of its technical parameters and policy parameters, especially, as a best-reply function to the SEPA's monitoring frequency i.e.,

$$C(\theta) = K + \frac{\beta}{2\alpha} - \frac{\theta t_p(\psi+\omega)}{2\alpha(1-t_y)} \geq 0 \tag{9}$$

and the consequent allocation for the productive capital is then

$$K - C(\theta) = -\frac{1}{2\alpha}\left[\beta - \frac{\theta t_p(\psi+\omega)}{1-t_y}\right] \geq 0 \tag{10}$$

and the consequent pollution intensity level will be

29. Otherwise, C = 0 is the firm's best choice.

$$P(\theta) = \psi[K - C(\theta)] - \omega C(\theta)$$
$$= -\frac{\beta}{2\alpha}(\psi + \omega) + \frac{\theta t_p(\psi + \omega)^2}{2\alpha(1 - t_y)} - \omega K \tag{11}$$

The above three equations, expressing the firms' optimal behavior in capital allocation and pollution control as parametric functions of the SEPAs' environmental policy, can be very useful for the SEPAs to set levels of their policy instruments. But what happens to the effective tax rate if a SEPA has a maximum tolerance level for pollution. It may be very patient and try to minimize its efforts to control pollution up to that level. Once that level is reached, how should the SEPA set the statutory tax rate and the monitoring effort? This is addressed next.

Policy Implication 3

If the SEPA has a maximum pollution tolerance level, denoted by P_c^I, and a positive expected (planned) monitoring rate $E(\theta) > 0$, then the SEPA will set a pollution tax rate at least as high as the "minimum required pollution tax rate", which is presented as

$$t_p^I = \frac{1 - t_y}{E(\theta)(\psi + \omega)^2}[\omega(2\alpha K+\beta) + \beta\psi + 2\alpha P_c^I] \tag{12}$$

This lower bound for the pollution tax rate guarantees that

$$(1 - t_y)(2\alpha K + \beta) < t_p^I E(\theta)(\psi + \omega) \tag{13}$$

This policy implication underlines another issue. If the FEPA sets a uniform pollution tax rate, then the SEPA will choose a minimum monitoring rate θ_m to ensure that the pollution level does not exceed the ceiling pollution tolerance level. Here,

$$\theta_m = \frac{1-t_y}{t_p(\psi+\omega)^2}[\omega(2\alpha K+\beta)+\beta\psi+2\alpha P_c^I] \tag{14}$$

Obviously, θ_m differs with the firms' production technology (as reflected by α and β), pollution intensity and abatement efficiency.

Policy Implication 4

With a positive nominal pollution tax rate, namely $t_p > 0$, the more frequently the SEPA inspects the firm's polluting behaviors, the more the firm will allocate to pollution control, as its effective tax rate on pollution increases.

This is true theoretically since from (9) we have:

$$\frac{dC(\theta)}{d\theta} = -\frac{t_p(\psi + \omega)}{2\alpha(1-t_y)} > 0 \tag{15}$$

In other words, if the SEPA increases its monitoring frequency, the firm will respond by investing more funds for environmental protection.

Policy Implication 5

With a positive inspection rate, namely, $\theta > 0$, raising either the value-added tax rate t_y or the pollution tax rate t_p will stimulate the firm to reduce pollution.

This can be verified from adjusting t_y and t_p in (9). In other words, raising t_y reduces the marginal cost of pollution control, while raising t_p increases the firm's marginal benefit of spending money for environment protection. In the model, both prompt the firm to increase investment in abatement. This in turn will lead to a reduction in pollution. This pollution reduction stems from the switch of capital from production to abatement. In practice, production may also be cut by reducing capacity utilization rather than by investing more in abatement. Pollution is cut either way but the state revenue effect will be quite different if the firm's strategy is to reduce utilization rather than increasing abatement. The model does not allow to assess the relative importance of this revenue effect.

Policy Implication 6

If the SEPA can manage to increase the efficiency of abatement (namely to increase ω), say by subsidizing research projects on environmental protection or by subsidizing the purchase of more efficient abatement technology by firms, then the firm will have more incentive to invest in pollution control.

Improving efficiency of pollution control investment is desirable since it increases the marginal benefit while keeps the marginal cost constant. This makes a strong case for subsidies as an instrument for pollution control. Within the framework develop here, however, it is clear that subsidies will only work if the firms are subject to a non-trivial effective tax rate. Furthermore the specific design or targeting of the subsidy is crucial determinant of its success.[30]

Policy Implication 7

Since increasing t_y, t_p, θ and ω has the same qualitative impact on the firm's optimal behavior, the SEPA can use: (i) tax rates, (ii) the inspection frequency and (iii) research subsidies as substitutes to induce the firm to cut the pollution it generates--assuming that the effective tax rate is above the minimum required rate.

To get insightful policy discussions, we concentrate on interior solutions of the firm's optimization problem where 0 < C < K. With C selected within these limits, the firm's output level can be regarded as a best-response correspondence to the SEPA's policy mix: $\theta \rightarrow Y(\theta)$. And we know

$$\frac{dY(\theta)}{d\theta} = \frac{dY}{d[K-C(\theta)]}\left(-\frac{dC(\theta)}{d\theta}\right) = \frac{\theta}{2\alpha}\left[\frac{t_p(\psi+\omega)}{1-t_y}\right]^2 < 0 \tag{16}$$

This confirms that an increase in the monitoring frequency (or the pollution tax rate) will lead to a lower output level, since more capital is reallocated for pollution control. Consequently, the pollution intensity will decline, i.e.,

$$\frac{dP(\theta)}{d\theta} = \psi\frac{d[K-C(\theta)]}{d\theta} - \omega\frac{dC(\theta)}{d\theta} = \frac{t_p(\psi+\omega)^2}{2\alpha(1-t_y)} < 0 \tag{17}$$

Changes in the expected pollution tax paid by the firm to the SEPA can be either positive or negative, depending on which effect dominates, namely,

$$\frac{d[t_p\theta P(\theta)]}{d\theta} = t_p P(\theta) + t_p\theta\frac{dP(\theta)}{d\theta} \tag{18}$$

30. This is not dealt with here, but for a fuller discussion, see Eskeland and Jimenez, op. cit.

The first term in (18) is the (positive) marginal gain due to the increased monitoring frequency, while the second term is the (negative) marginal loss due to the shrunk pollution tax basis. However, if we look at the elasticity of pollution tax revenue with respect to a marginal increase of the monitoring rate, we have

$$\frac{\theta}{t_p \theta P(\theta)} \cdot \frac{d[t_p \theta P(\theta)]}{d\theta} = \frac{1}{t_p P(\theta)}\left[t_p P(\theta) + t_p \theta \frac{dP(\theta)}{d\theta}\right] \\ = 1 + \frac{\theta}{P(\theta)} \frac{dP(\theta)}{d\theta} \tag{19}$$

Therefore, the elasticity of pollution tax revenue is positively correlated with the elasticity of pollution level with respect to the change of the SEPA's monitoring frequency. More specifically, the absolute values of the two elasticities sum to 1.

2. The SEPA's Problem

Let F denote the lump-sum penalty imposed by the FEPA upon the SEPA if the FEPA discovers that the SEPA does not monitor the firm's performance on pollution control. In practice, the FEPA could for instance go to a river in a highly polluted region and check water quality. If pollution is in excess of federal standards, the SEPA is fined, irrespective of the source. The FEPA should not have to worry about the specific sources of pollution, ambient quality control should be sufficient.

Let η ($0<\eta<1$) denote the probability that the FEPA audits the SEPA. The probability would be 1 if for instance the FEPA checks the water once a week. Any reduction in the frequency reduces the probability. Then the SEPA's expected net tax revenue can be written as

$$R(\theta;\eta) = t_y Y(\theta) + t_p \theta P(\theta) - \theta M - (1-\theta)\eta F \tag{20}$$

where M is the monitoring cost of the SEPA. Equation (20) reflects the fact that total revenue from the VAT and the pollution tax need to be adjusted for SEPA's monitoring costs and for fines paid by the states for violation of FEPA's directives. Since the SEPA acts as the Stackelberg leader in its relationship with the firm, Y, P and C in (20) are functions of θ. For any given η and the firm's responses, the SEPA selects its monitoring frequency to maximize its expected net tax revenue. Take the first derivative of the SEPA's objective function, we have

$$\frac{dR(\theta;\eta)}{d\theta} = t_y \frac{dY(\theta)}{d\theta} + t_p\, P(\theta) + t_p \theta \frac{dP(\theta)}{d\theta} - M + \eta F \tag{21}$$

The second derivative of $R(\theta;\eta)$ with respect to θ is

$$\frac{d^2R(\theta;\eta)}{d\theta^2} = \frac{t_y}{2\alpha}\left[\frac{t_p(\psi+\omega)}{1-t_y}\right]^2 + \frac{t_p^2(\psi+\omega)^2}{\alpha(1-t_y)} < 0 \tag{22}$$

So, the second order condition is satisfied for all feasible values of θ. Hence, the SEPA's optimal choice of θ is determined from the following equation

$$M - \theta\left(\frac{t_y}{2\alpha}\left[\frac{t_p(\psi+\omega)}{1-t_y}\right]^2 + \frac{t_p^2(\psi+\omega)^2}{2\alpha(1-t_y)}\right) = \eta F + t_p P(\theta) \tag{23}$$

which equalizes the SEPA's marginal cost and marginal benefit of inspecting the firm's polluting behaviors. Here, the SEPA's marginal cost is the left hand side of (23). The marginal benefit is the right hand side. It is easy to verify from (11) and (23) that the SEPA's marginal cost of monitoring is (linearly) increasing with θ while its marginal benefit is (linearly) decreasing with θ.

Substitute (11) into (23), we can get:

$$\theta = \min\left[1, \max\left(0,\ \frac{2\alpha\left(t_p\omega K + \frac{\beta t_p(\psi+\omega)}{2\alpha} - \eta F + M\right)(1-t_y)^2}{(2-t_y)\ t_p^2(\psi+\omega)^2}\right)\right] \tag{24}$$

The max-operator in the inner bracket rules out possible negative solutions. The outside min-operator excludes any solution with θ being greater than 100%. The SEPA's optimal choice of θ can be in three possible cases, as graphed in Figure 4. In case (i), the SEPA's marginal cost of monitoring is larger than its corresponding marginal benefit at $\theta = 0$. This is equivalent to stating that

$$\eta F < M + t_p\,\omega\, K + \frac{\beta t_p(\psi + \omega)}{2\alpha} \tag{25}$$

So, the SEPA will rationally choose "not to monitor" the firm's pollution behavior. This case can be true when (a) the SEPA's monitoring cost is too high, (b) the penalty paid to the FEPA is not significant, or (c) the FEPA's environmental policy is heavily discounted by its low inspection rate. On the other hand as in case (iii), the SEPA's marginal cost of monitoring is relatively low even at $\theta = 1$. Hence, the SEPA will always feel it beneficial to conduct an inspection to push the firm to invest for pollution control.

When the solution to the SEPA's maximization problem is interior in (0,1), then we have

$$\frac{d\theta}{d\eta} = \frac{-2\alpha}{2-t_y}\left(\frac{1-t_y}{t_p(\psi+\omega)}\right)^2 F > 0 \tag{26}$$

and

$$\frac{d\theta}{dF} = \frac{-2\alpha}{2-t_y}\left(\frac{1-t_y}{t_p(\psi+\omega)}\right)^2 \eta > 0 \tag{27}$$

Hence, we have the following policy implications.

Policy Implication 8

An increase in the penalty level F or in the inspection rate η will raise the SEPA's incentive to comply with the environmental law by increasing its own monitoring frequency, thus reduce the pollution intensity in the environment.

This is follows from equation (17) and (26):

$$\frac{dP}{d\eta} = \frac{dP}{d\theta}\frac{d\theta}{d\eta} = -\frac{1-t_y}{t_p(2-t_y)} < 0 \tag{28}$$

In fact, a bigger F implies a larger marginal benefit for the SEPA to monitor the firm's pollution behavior.

Policy Implication 9

A reduction in the SEPA's monitoring cost, M, will stimulate the SEPA to monitor more frequently. This suggests that well targetted federal subsidies should be considered as a possible instrument to reduce pollution.

This can be verified by taking the first order condition of the SEPA's optimization problem as an implicit function, and

$$\frac{d\theta}{dM} = \frac{2\alpha}{2-t_y}\left(\frac{1-t_y}{t_p(\psi+\omega)}\right)^2 < 0 \tag{29}$$

This policy implication suggest that federal subsidies in the form of matching grants for instance would contribute to an improved monitoring performance if it were allocating to cost reducing investments by firms. Figure 5 above graphically illustrates these two policy implications.

Policy Implication 10

If the FEPA has a maximum standard for the pollution intensity in the environment, then it can set a set of appropriate penalty level and inspection rate such that its target on environment protection can be achieved through behavior adjustments of the SEPA and the pollution-generating firm.

This implication can be understood by checking backward through the players' reaction chain. From (11), we know that the pollution intensity, P, is determined once the firm made its portfolio decision on how much to invest for pollution control, which in turn is a response of the SEPA's tax-monitoring policy. Meanwhile, from (24), we see that the SEPA's optimal selection of monitoring frequency is a response function of the FEPA's policy mix. Therefore, the pollution intensity level P is a composite response function of F and η. For any given ceiling standard for pollution intensity, say P^c, the FEPA can figure out a floor requirement for the SEPA's monitoring rate, denoted by θ_f. Then, with other technical and policy parameters pre-determined, the FEPA can calculate a combination of η and F such that the SEPA's choice of θ is at least as high as θ_f. In this manner, the pollution intensity in the environment can be controlled under the pre-set target level P^c. This policy-making procedure is incentive compatible.

To ensure that the regional authority fully comply with the environmental law (i.e., $\theta = 1$), the FEPA has to set an effective penalty level satisfying the following condition

$$\eta F \geq M + t_p\, \omega\, K + \frac{\beta t_p(\psi + \omega)}{2\alpha} - \frac{(2-t_y)\, t_p^2(\psi + \omega)^2}{2\alpha(1-t_y)^2} \tag{30}$$

Inequality (30) provides a guideline for the FEPA to set a penalty level for any given expected (planned) inspection rate.

3. The FEPA's Problem

A growth-oriented FEPA likes the firm's total output but dislikes the pollution it generates. This preference, commonly represented as a social welfare function, can be written as a simple objective function of the FEPA, i.e.,

$$U(Y,P) = Y - \lambda p(Y,C) + \eta[\,(1-\theta)F - m\,] \tag{31}$$

where m is the FEPA's inspection cost and λ is the FEPA's relative disutility of the pollution, which converts the FEPA's dislike of pollution in terms comparable with GNP figures. The value of λ is determined by the society's pressure or some other socio-economic factors. From (31), we can see that

$$\lambda = \left.\frac{dY}{dP}\right|_{u=u_0} \tag{32}$$

i.e., λ is the FEPA's marginal substitution rate between output and pollution, which keeps the FEPA's utility level constant. The FEPA's influence on the firm is indirect through the SEPA. As the up-most Stackelberg leader in the game, the FEPA knows how the SEPA would respond to its own policy selection. Substitute the SEPA's response function into the FEPA's utility function, we can write the FEPA's objective function as

$$U = u(\eta) = Y[\theta(\eta)] - \lambda P[\theta(\eta)] + \eta\{[1-\theta(\eta)]F - m\} \tag{33}$$

Take the first derivative of u, we get

$$\frac{du}{d\eta} = \frac{dY}{d\theta}\frac{d\theta}{d\eta} + [(1-\theta)F-m] - \eta F\frac{d\theta}{d\eta} - \lambda\frac{dP}{d\theta}\frac{d\theta}{d\eta} \tag{34}$$

From (15), (16) and (17), we obtain

$$\begin{cases} \dfrac{d^2\theta}{d\eta^2} = 0 \\ \dfrac{d^2Y}{d\theta^2} = \dfrac{1}{2\alpha}\left[\dfrac{t_p(\psi+\omega)}{1-t_y}\right]^2 < 0 \\ \dfrac{d^2P(\theta)}{d^2\theta} = 0 \end{cases} \tag{35}$$

So, the second order condition for the FEPA's maximization problem is satisfied for all η in [0,1], since

$$\begin{aligned} \frac{d^2u}{d\eta^2} &= \left(\frac{d^2Y}{d\theta^2} - \lambda\frac{d^2P}{d\theta^2}\right)\left(\frac{d\theta}{d\eta}\right)^2 + \left(\frac{dY}{d\theta} - \eta F - \lambda\frac{dP}{d\theta}\right)\frac{d^2\theta}{d\eta^2} - 2F\frac{d\theta}{d\eta} \\ &= -2F\frac{d\theta}{d\eta} + \frac{d^2Y}{d\theta^2}\left(\frac{d\theta}{d\eta}\right)^2 < 0 \end{aligned} \tag{36}$$

The FEPA selects its best monitoring policy by solving η from the following equation

$$MC = m - \frac{dY}{d\theta}\frac{d\theta}{d\eta} + \eta F\frac{d\theta}{d\eta} = [1-\theta(\eta)]F - \lambda\frac{dP}{d\theta}\frac{d\theta}{d\eta} = MB \tag{37}$$

Treat (37) as an implicit function relating policy parameters of both the FEPA and the SEPA, we have

$$\frac{\partial\eta}{\partial\lambda} = -\frac{\dfrac{d^2u}{d\eta\, d\lambda}}{\dfrac{d^2u}{d\eta^2}} = -\frac{-\dfrac{dP}{d\theta}\dfrac{d\theta}{d\eta}}{-2F\dfrac{d\theta}{d\eta} + \dfrac{d^2Y}{d\theta^2}\left(\dfrac{d\theta}{d\eta}\right)^2} > 0 \tag{38}$$

Policy Implication 11

The more the FEPA dislikes pollution, the more frequently the FEPA will monitor the SEPA's performance. Consequently, the pollution intensity level in the environment will be reduced.

This can be seen from

$$\frac{dP}{d\lambda} = \frac{dP}{d\theta}\frac{d\theta}{d\eta}\frac{d\eta}{d\lambda} < 0 \tag{39}$$

Policy Implication 12

Reducing the FEPA's inspection cost will contribute to alleviate environmental pollution.

This follows from:

$$\frac{d\eta}{dm} = -\frac{\dfrac{d^2u}{d\eta\, dm}}{\dfrac{d^2u}{d\eta^2}} = \frac{1}{-2F\dfrac{d\theta}{dy} + \dfrac{d^2Y}{d\theta^2}\left(\dfrac{d\theta}{d\eta}\right)^2} < 0 \tag{40}$$

and

$$\frac{dP}{dm} = \frac{dP}{d\theta}\frac{d\theta}{d\eta}\frac{d\eta}{dm} > 0 \tag{41}$$

APPENDIX Data Issues

A.1. Data scarcity heavily confines the scope and quality of empirical tests of our theoretical modelling. Information on pollution intensity and its relevant economic statistics are hardly available in most developing countries. Even though we can get some data from different sources, it is difficult to evaluate their reliability. Sometimes they are simply incomparable. Therefore, cautions must be taken when we interpret our empirical results. Brazil's persisting hyperinflation further complicates our data mining.

A.2. To conduct numerical policy simulations, we need two types of data. The first reflects the economy's statistical characteristics, generally influenced by government policies but not directly controlled by the government. These include the parameters in the firm's production function. The second type of data are the policy instruments. Either the federal or the state governments can set them. These include tax rates, monitoring levels and penalty levels. They can be used to perform sensitivity analysis. The interactions between these two types of data provide the basis for our simulation work.

A.3. More specifically, the characterization of the variables and data requirements is as follows:

Exogenous Variables

K: the total sectoral capital stock
Y: the value-added output level
P: the pollution intensity index, which is the total toxic release into the environment

Technical Parameters

α, β and γ: the efficiency index of the productive capital
ψ: the pollution rate of the productive capital
ω: the abatement rate of the investment for pollution control

Policy Parameters:

t_y: the value-added tax rate
t_p: the pollution tax rate
M: the inspection cost of the SEPA
m: the inspection cost of the FEPA
F: the penalty the SEPA pays to the FEPA if the SEPA is discovered "cheating"
λ the coefficient for the FEPA's relative disutility of the pollution

Endogenous Variables:

C: the firm's optimal choice of investment for pollution control,
Y^*: the value-added output when investment for pollution control is allocated,
P^*: pollution intensity the firm generates when investment for pollution control is allocated,
R^*: the SEPA's tax revenue at equilibrium
θ: the inspection frequency for the SEPA
η: the inspection frequency for the FEPA
U^* the social welfare function at equilibrium

A.4 Estimation of quadratic production functions

This section provides rough estimates of sectoral production functions for two industrial sectors in Brazil. One of them is a "dirty industry" according the Wheeler classification, the other is a mildly polluting or toxic sector. The first is printing and publishing, the second is food.

For each sector, from the Brazilian Statistical Office publication on historical series, IBGE, we have 11 observations on the sectoral investment, value-added and gross output from 1970 to 1980. From in the 1970 and 1980 input-output matrix, we extracted the capital stock. Relying on the investment series and deriving an average depreciation by comparing the 1970 and 1980 capital stocks, we reconstructed the annual capital stock. All variable are expressed in 1987 dollars. A quadratic production function with three parameters is estimated for each sector at degree of freedom 8. The results of OLS estimation are presented below. The figures in the brackets are the t statistics for the estimated parameters.

(a) Food

$$Y = -\underset{(-2.3)}{0.00000017}\,(K-C)^2 + \underset{(3.4)}{2.9788}\,(K-C) - \underset{(-2.6)}{6396533} \qquad R^2 = 0.953$$

(b) Printing and Publishing

$$Y = -\underset{(3.3)}{0.0000033}\,(K-C)^2 + \underset{(3.8)}{6.8019}(K-C) - \underset{(15.4)}{1913619} \qquad R^2 = 0.86$$

At 90% significance level, the t-statistic with 8 degree of freedom for all estimated parameters are required to be greater than 2.2 to accept the hypothesis that the parameters are significantly different from zero. These unconstrained estimates satisfy our a priori parameters requirements.

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